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LUMPED NODE THERMAL MODELING OF EMA WITH FEA VALIDATION (PREPRINT)

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Abstract concludes on reverse →

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In this paper we present an FEA-based lumped node network and its simulation of a mission profile. This model is based on a detailed FEA model to locate the hot spots, to determine the network parameters and to verify its effectiveness. The model can also deal with the nonlinear behavior of the EMA system introduced by phase-change materials (PCM) if thermal energy storage is needed, and temperature-dependent magnetic properties. This model can also be incorporated into lumped node magnetic and electric model to develop a full multi-physics, multi-scale simulation engine. This engine can accurately analyze the complete EMA system in a systematic scale and whole-mission duration.

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Lumped Node Thermal Modeling of EMA with FEA Validation

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INTRODUCTION

The application of EMA on military aircraft poses a challenge in the design of the whole driving train, from the motor-controller to the gearbox. To successfully replace the hydraulic counterparts, the EMAs have to provide reliable driving force in whole mission profile under the thermal, power, mass and size constraints. In addition, the EMA performance, reliability and power consumption depend on the temperatures of the key components, including the power electronics and electric motor. Waste heat, if not properly managed, could cause high temperatures of the motor-driver, motor and gearbox, leading to performance degradation, and creating even more power losses, and hence would increase the temperatures even more. A complete multi-physics simulation study for a realistic mission profile is essential to fully understand the performance of the EMAs on aircraft.

Finite Element Analysis (FEA) is widely used in today's mechanical, electronic and aerodynamic designs. However, direct application of FEA to analyze the whole EMA system would require tremendous amount of computational power. An estimate of one-hour duration of FEA transient thermal simulation of an electric motor requires two terabytes of hard drive disk space and 720 hours of CPU time on a typical quad-core computer. The whole EMA model is more complex than the electric motor and consequently requires even more computational resources. A multi-physics FEA simulation, including electronics, magnetics and stress calculations would make such a simulation impractical, especially when real-time information is needed.

Another approach is to develop a lumped node thermal network to represent the temperature of every solid part of the EMA. The thermal resistances and capacitances between the nodes can be treated as electrical resistances and capacitances. Hence the temperature of every node can be solved as the voltage in this equivalent network (Table 1). This approach is well developed in motor design industry [1, 2]. Some commercial motor design software package has already

included the thermal network simulation, i.e. Motor-CAD [3]. Some studies have been made with FEA analysis and experimental testing have shown that such an approach is valid [4].

Electrical Circuit			Thermal Circuit		
V	$[V]$	Voltage	T	$[^oC]$	Temperature
I	$[A]$	Current Flow	Q	$[W]$	Heat Flow
σ	$[1/\Omega m]$	Electrical Conductivity	κ	$[W/^oCm]$	Thermal Conductivity
R	$[\Omega]$	Resistance	R^θ	$[^oC/W]$	Thermal Resistance
C	$[F]$	Capacitance	C^θ	$[J/^oC]$	Thermal Capacitance

Table 1. The analogy of the equivalent thermal circuit

$$R^{\theta}{}_{conductive} = \frac{\Delta X}{k * A_{contact}}$$
$$R^{\theta}{}_{convective} = \frac{1}{h * A_{surface}} \tag{1}$$

$$C^{\theta} = \rho * V * C_p \tag{2}$$

Equations 1 and 2 show how to calculate the R and C values for simple one-dimensional geometry. Accurate estimates for R and C values are not possible for complicated geometries such as an electric motor. The traditional lumped node thermal network is based on a “forward” direction modeling process. In this process, with all the material, geometry and construction information provided, the thermal resistance Rθ and capacitance Cθ are calculated based on empirical and theoretical relations. For example, when the winding wire type, winding structure, potting material, slot width and teeth thickness are given, the thermal resistance from winding to stator and from winding to rotor can be calculated. Because this type of approach requires large number of empirical relations to achieve high accuracy, a “reverse” modeling process is introduced in this paper. A detailed 3-D solid model of a target motor is constructed and imported to an FEA software like ANSYS [5] to perform steady-state and transient simulation. With these results we can estimate and select the values for the thermal resistances and capacitances. The advantage of this method is that we can evaluate the fidelity of the lumped node model with a real motor, add or reduce nodes to increase the model accuracy and efficiency, and estimate the maximum error between the node temperature and maximum temperature in real motor.

This procedure can also be extended to model the gear-box, motor-driver and drive-train, and even include the aircraft wing surfaces and frames. The thermal network can also be

incorporated into a multi-physics model to simulate the electrical, thermal and mechanical performance of the whole EMA and its supporting structure. Once the proper thermal resistances and capacitances are selected, this simulation engine can be used with various time dependent boundary conditions during the whole mission duration, including the air temperature, aircraft speed, altitude and sunlight. The computational requirement of such a simulation is negligible compared to the FEA simulation.

MODELING

Figure 1 is the 3-D model of a typical Permanent Magnet Synchronous Machine (PMSM) servo motor. This design features a 12-slot stator and a 10-pole rotor (Figure 2). This motor is designed to input 10 hp electrical power, with a efficiency of 91.8%. The total power loss in the motor is 611W. In the computation domain (Figure 1) the power loss is 153W. The distribution of the power loss in the motor components is listed in Table 3. In Figure 1 the parts are numbered in the same way as in Table 2. These numbers are also the same as those in the lumped node network shown in Figures 6 and 7.

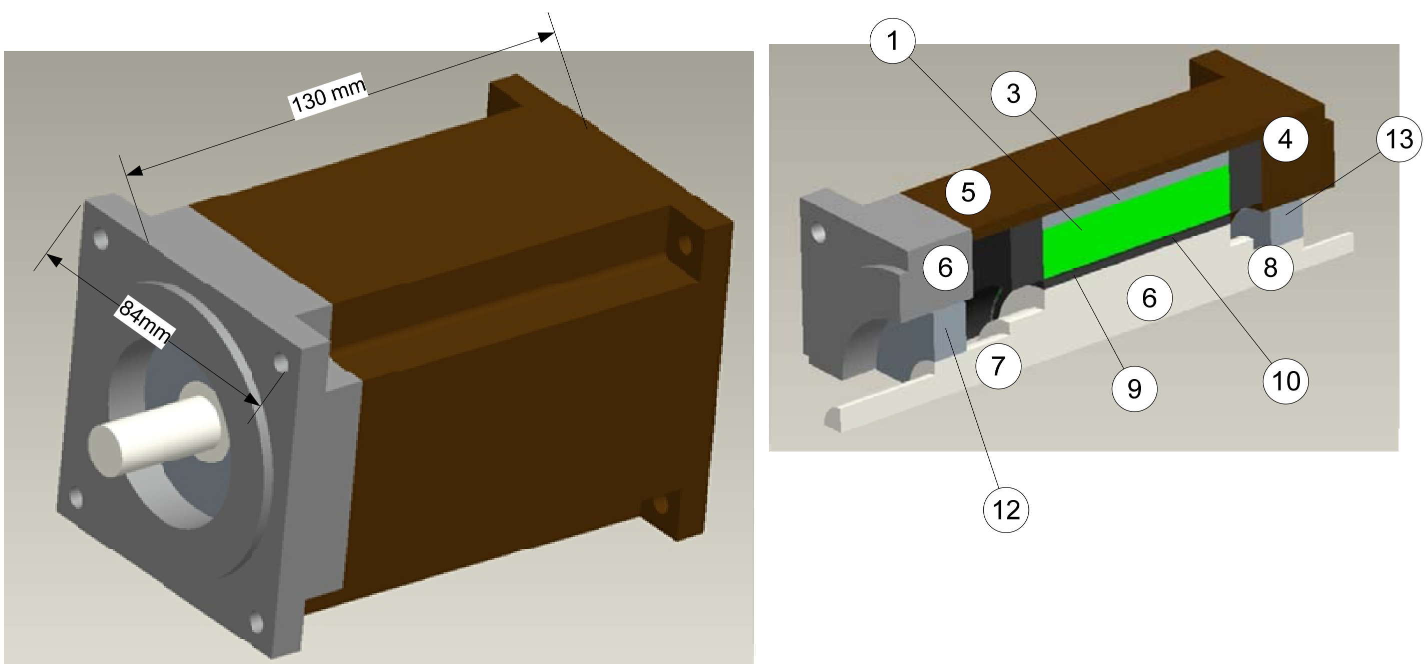

Figure 1. 3-D model of the PMSM motor design and computation domain.

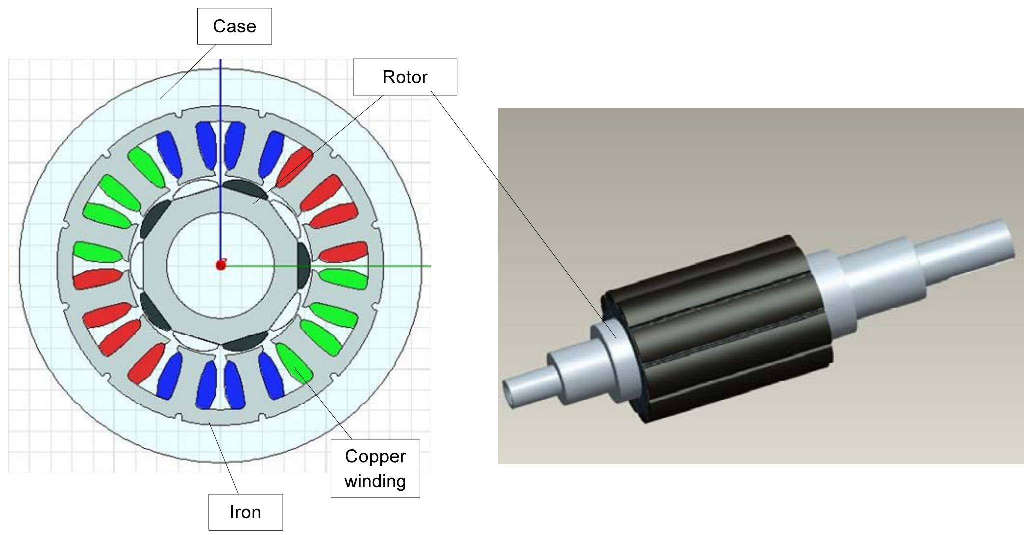

Figure 2. Cross-section of motor and rotor.

Due to the symmetry, the geometry of the model is divided into a quarter section and imported into ANSYS for the FEA simulation. A total thermal load given in Figure 4 and with heat distribution shown in Table 3 are assumed. An external forced convective heat transfer coefficient of 100 W/m2.K applied to the case of the motor. Figures 3 and 5 show the steady-state temperature field and the transient temperature response inside the windings and rotor magnet.

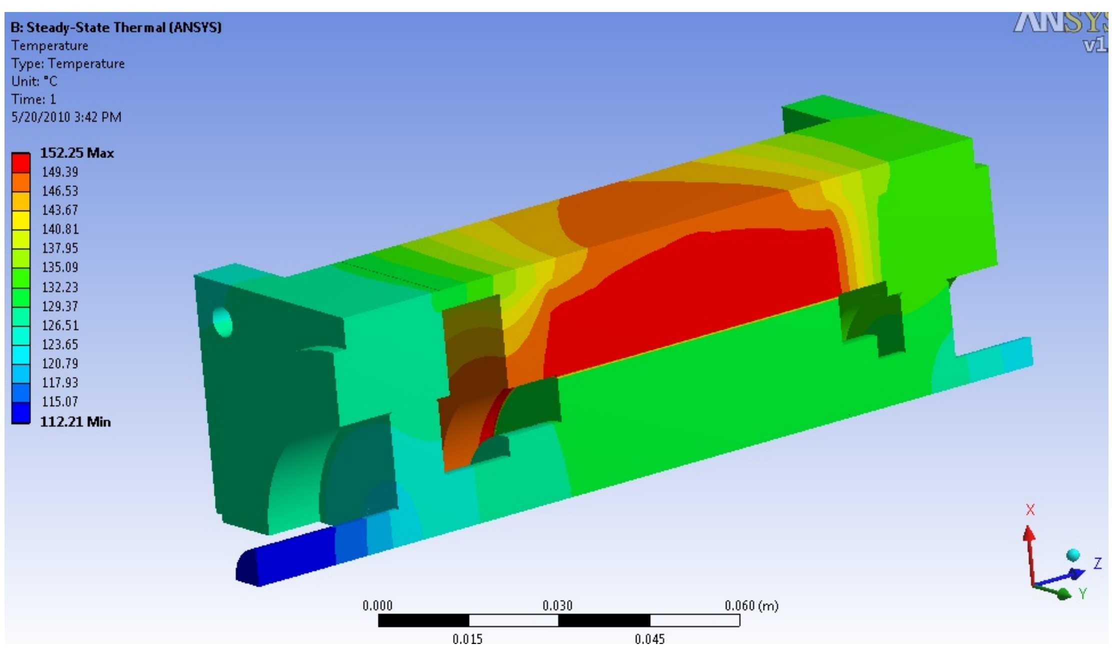

Figure 3. Steady state thermal simulation result (forced convection).

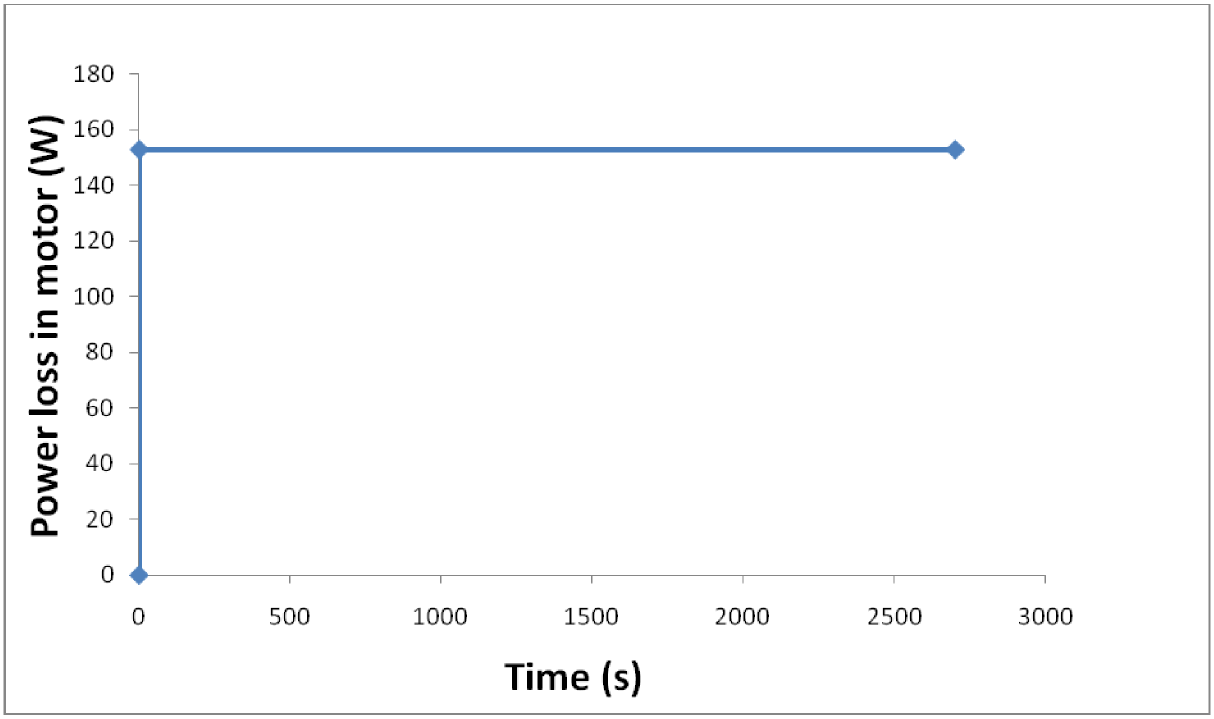

Figure 4. Step heat load of the motor

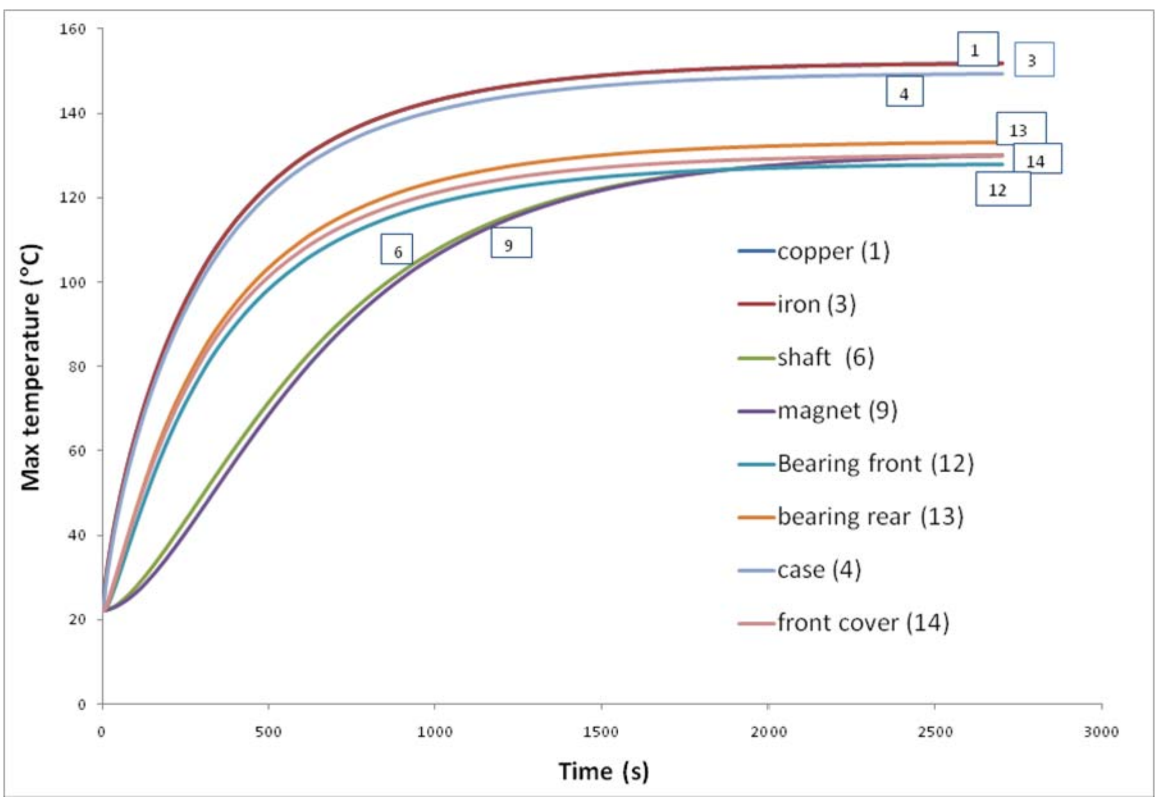

Figure 5. Transient temperature response of the load in Figure 4

ANSYS (or any other FEA software) generally gives temperature information in the whole calculation domain. However, in practice, only several locations or components are needed to assess the thermal behavior of the motor. For the problem at hand, we focus only on the temperatures of the winding, stator, magnet and bearing. It is noted that for every component, the temperature is not uniform. The temperature range can be characterized by the maximum and minimum temperatures within the particular component. For the copper winding, these two temperatures are quite close because of the excellent thermal conductivity of copper. While in the stator these two temperatures differ by a few degrees. In the lumped node network we only use a single value to represent each component, which generally is the average temperature. The deviation between the average temperature and the maximum temperature in the components should be kept in mind in the lumped node simulation.

The node network is constructed as shown in Figure 6. The electric motor is assumed to have 3 major thermal paths with other parts of EMA and environment. The first one is the thermal resistance R5, which represents the convection thermal resistance between motor surface and the air around it. Considering that the motor will be installed in a small space inside the wing structure, this convection is likely to be natural convection or weak forced convection. In ANSYS we assume the heat transfer coefficient for the forced convection to be h=100 W/m2.K, which is a typical value for forced convection in air (Figure 3). The value of R5 can be easily changed to accommodate the actual flow situation in the motor's final installation and flow conditions.

The second thermal path is the conductive heat transfer from the motor front cover to gear-box, which is represented as R17. The third one is the conductive heat transfer from the motor rotor to the gear mechanism. The third one, R7a, could be a minor heat flow path because the rotor and bearing loss is relatively small. But there is a possibility that the gear mechanism has higher temperature than the rotor and conduct heat back to motor. There could be additional thermal paths, such as from the motor back plate to the aircraft frame, which are not shown in Figure 6. However, incorporating additional thermal paths into the network and changing the lumped-node model accordingly is simple with the method presented in this paper.

The following procedure is used to determine the R and C values in the lumped node network of motor assembly shown in Figure 6. Table 2 lists all the nodal temperatures from ANSYS steady state simulation for motor with natural and forced convection boundary conditions. In this Table, the temperatures with the presence of radiation heat transfer is also considered and listed. It should be noted that in a situation where air cooling is not effective (such as natural convection with a low h), the motor temperature could be very high and radiative heat transfer becomes the

dominant mode of heat transfer. However when there is more effective convective heat transfer, the radiation becomes a minor heat path. For forced convection, the Nusselt number for a cylinder is determined from[6],

$$\overline{Nu_D} = CRe_D^m Pr^{1/3} \tag{3}$$

where C and m are based on the Reynold's number. However, it is difficult to determine the flow condition and the characteristic length of the motor and drive bay. In this paper, a high h value of 100 to represent force convection flow is used and radiation is not included. A comparative low convective transfers coefficient (h=10) case is also listed in table 2 to show the dominance of radiative heat transfer in that situation. The radiation thermal path can be easily included by adding a radiative thermal resistance to the lumped node model when it is necessary. The h value can also be easily altered based on the working condition of the motor installed without any change of other parameters of the motor thermal model.

Table 2 and the power loss table (Table 3) are combined to solve the steady state lumped node network. (Figure 7)

Node name	Material	Node number	Temp. (h=100) in °C (w/o Rad.)	Temp. (h=100) in °C (w/ Rad. ε=0.85)	Temp. (h=10) in °C (w/o Rad.)	Temp. (h=10) in °C (w/ Rad. ε=0.85)
Copper winding	Copper	1	162	153	1229	396
Epoxy	Epoxy	2	161	152	1228	395
Iron stator	Iron	3	161	152	1228	395
Case	Aluminum alloy	4	152	145	1220	385
Case surface		5	150	143	1218	382
Front cover	Aluminum alloy	14	141	131	1210	377
Shaft	Stainless Steel	6	149	139	1216	384

Shaft front end	Stainless Steel	7	145	138	1214	383
Shaft back end	Stainless Steel	8	148	138	1214	383
Magnet	NdFeB	9	149	140	1217	385
Airgap	Air	10	160	151	1227	395
Front bearing	Steel	12	143	135	1212	381
Rear bearing	Steel	13	147	137	1212	381

Table 2. Steady state simulation results with ANSYS

	Power loss (W)	Percentage of total power loss
IC (copper loss)	144	94.33%
IS (stator loss)	6.06	3.97%
IM (magnet loss)	0.86	0.56%
IW (windage loss)	0.35	0.23%
IBF (front bearing loss)	0.84	0.55
IBB (rear bearing loss)	0.54	0.35%

Table 3. Component heat generation

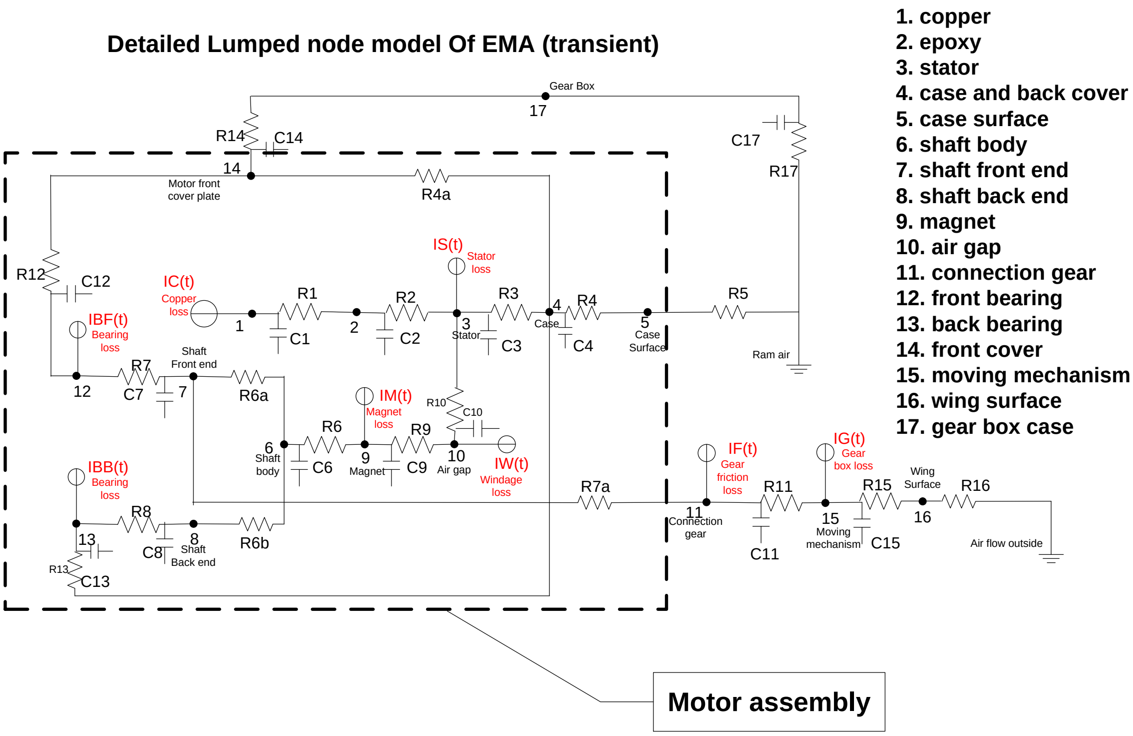

Figure 6. Lumped node model of EMA (transient)

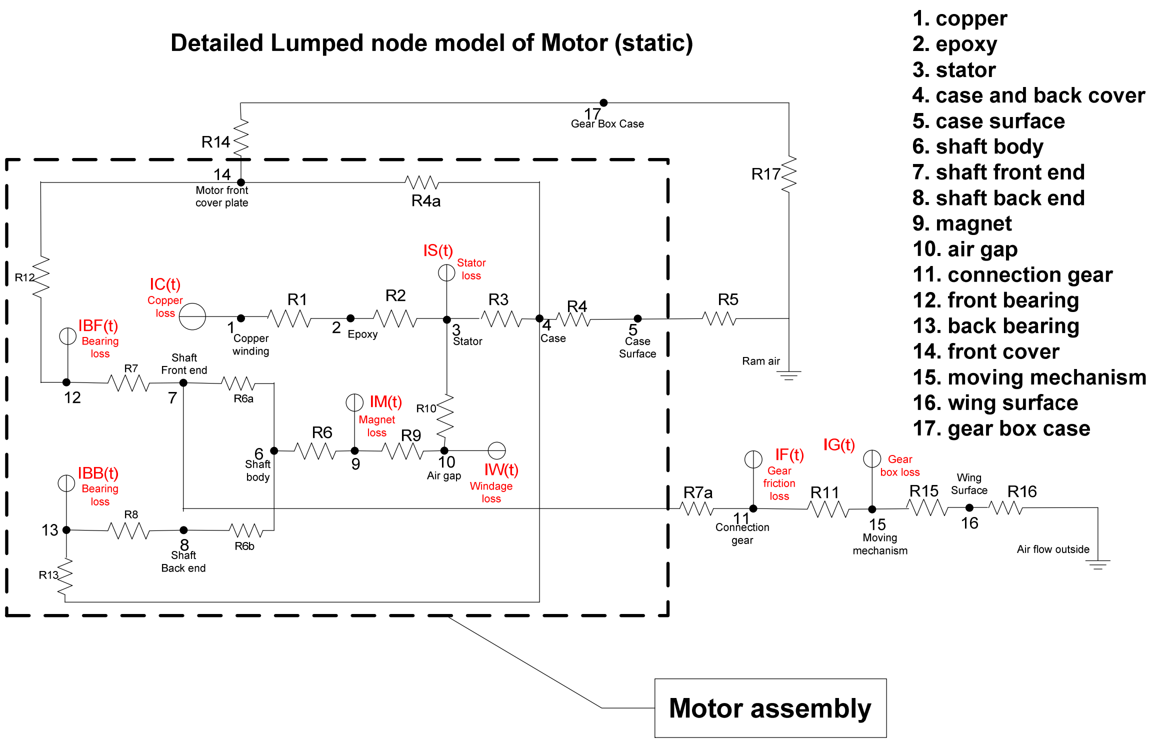

Figure 7. Lumped node model of EMA (steady state)

For a pure resistance network with all the voltages and currents sources known, the standard procedure is to apply Kirchhoff's Current Law (KCL) equations to every node. However, the number of nodes is generally less than the number of resistances, which means there are not enough equations to solve for the resistances. One solution is to add additional heat flux conditions from ANSYS. In this case, heat flux through R10, R7 and R8 are added. After that, the thermal capacitance values can be calculated from Equation 2. Table 4 lists the R and C values used in the lumped node model.

R1	°C/W	0.001155	R4	°C/W	0.001891
R2	°C/W	0.00042	R4a	°C/W	0.53
R3	°C/W	0.0527	R6	°C/W	0.0857
R5	°C/W	0.72	R6b	°C/W	1.022
R6a	°C/W	1.03	R7	°C/W	0.51
R10	°C/W	8.49	R8	°C/W	0.47
R12	°C/W	1.61	R9	°C/W	20.933
R13	°C/W	2.456	R14a	°C/W	3.75
C1	J/°C	35.68	C4	J/°C	235.1
C2	J/°C	16.47	C7	J/°C	14.99
C3	J/°C	59.3	C8	J/°C	7.08
C6	J/°C	56.03	C10	J/°C	0.00176
C9	J/°C	6.72	C14	J/°C	62.56
C13	J/°C	6.72	C12	J/°C	13.18

Table 4. The R and C values of lumped node model of the motor assembly shown in Figure 6

LUMPED NODE MODEL SIMULATION

After all the resistor and capacitor values of the lumped-node network model of the motor in Figure 6 are known, the same values of the resistors and capacitors can be used to simulate the temperature response of the motor parts with any combination of heat losses and boundary conditions. For this standard resistor-capacitor electrical network, a set of first-order ordinary differential equations can be written as (Eq. 3-Eq. 13), where the variable U represents the node temperature.

$$\frac{U1-U2}{R1}+C1\frac{dU1}{dt}=IC(t) \tag{4}$$

$$\frac{U2-U3}{R2}+C2\frac{dU2}{dt}-\frac{U1-U2}{R1}=0 \tag{5}$$

$$\frac{U4-U3}{R3}+\frac{U10-U3}{R10}-\frac{U1-U3}{R1}+C3\frac{dU3}{dt}=IS(t) \tag{6}$$

$$(R9+R10)U10=U3R9+R10U9+R9R10IW(t) \tag{7}$$

$$\frac{U6-U8}{R6b}-\frac{U13-U8}{R8}-C8\frac{dU8}{dt}=0 \tag{8}$$

$$\frac{U13-U4}{R13}-\frac{U13-U8}{R8}+C13\frac{dU13}{dt}=IBB(t) \tag{9}$$

$$\frac{U14-U4}{R4a}+\frac{U13-U4}{R13}+\frac{U4-U3}{R3}-\frac{U4-U5}{R4}-C4\frac{dU4}{dt}=0 \tag{10}$$

$$\frac{U12-U14}{R12}+\frac{U7-U12}{R7}-C12\frac{dU12}{dt}=IBF(t) \tag{11}$$

$$\frac{U9-U6}{R6}-\frac{U10-U9}{R9}+C9\frac{dU9}{dt}=IM(t) \tag{12}$$

$$\frac{U6-U7}{R6a}+\frac{U6-U8}{R6b}-\frac{U9-U6}{R6}+C6\frac{dU6}{dt}=0 \tag{13}$$

$$\frac{U7-U12}{R7}-\frac{U6-U7}{R6a}+C7\frac{dU7}{dt}=-IR7a \tag{14}$$

$$\frac{U12-U14}{R12}-\frac{U14-U4}{R4a}+C14\frac{dU14}{dt}=IR14 \tag{15}$$

This equation set can be solved by standard numerical methods. In Figure 8 the simulation results of the lumped node model are compared with the FEA results under same initial condition and boundary conditions.

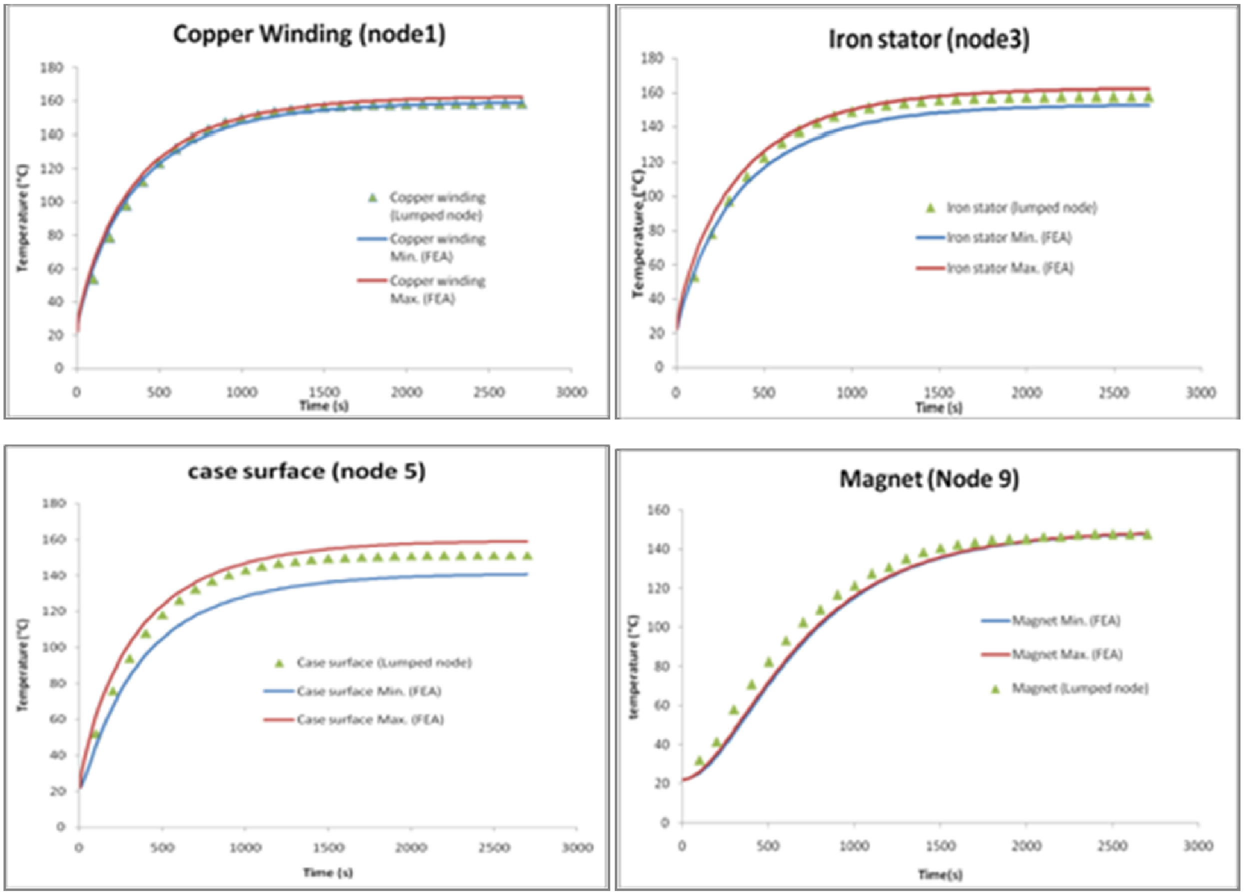

Figure 8. Lumped-node network simulation result

The results show excellent accuracy in both steady state and transient response for the step heat load given in Table 3 and Figure 4. This model is also tested with pulsed load, where the thermal load is a square wave form repeated with time, as shown in Figure 9. We compared the resulting temperature change in copper winding of the motor (Figure 10).

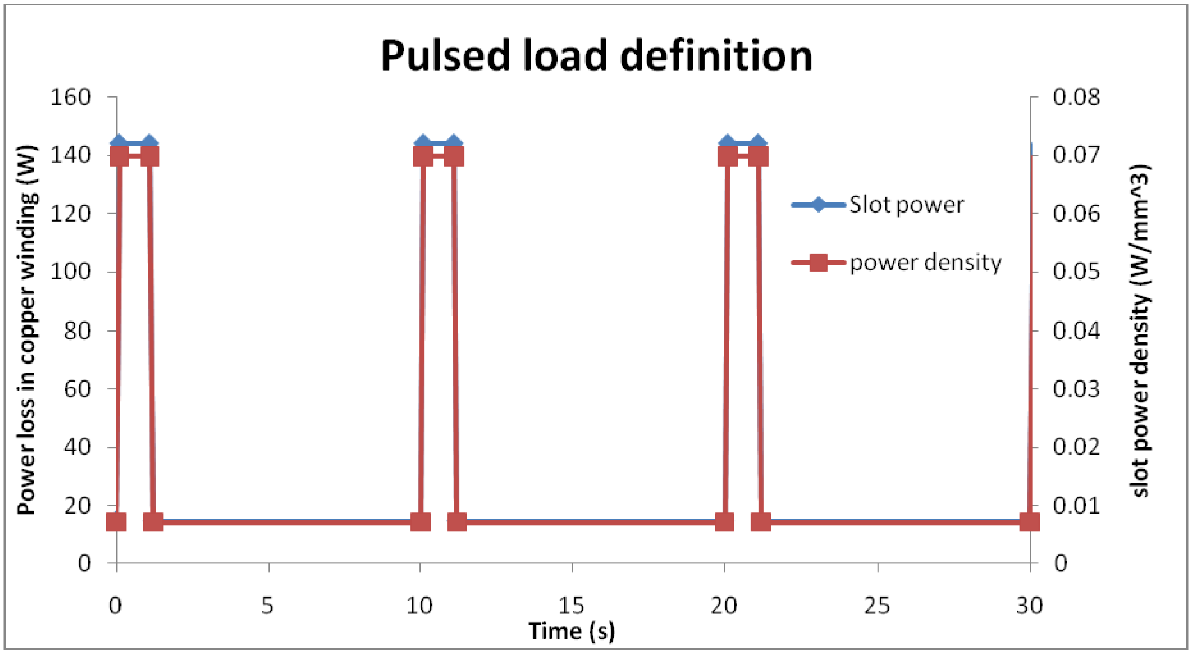

Figure 9. Pulsed heat load

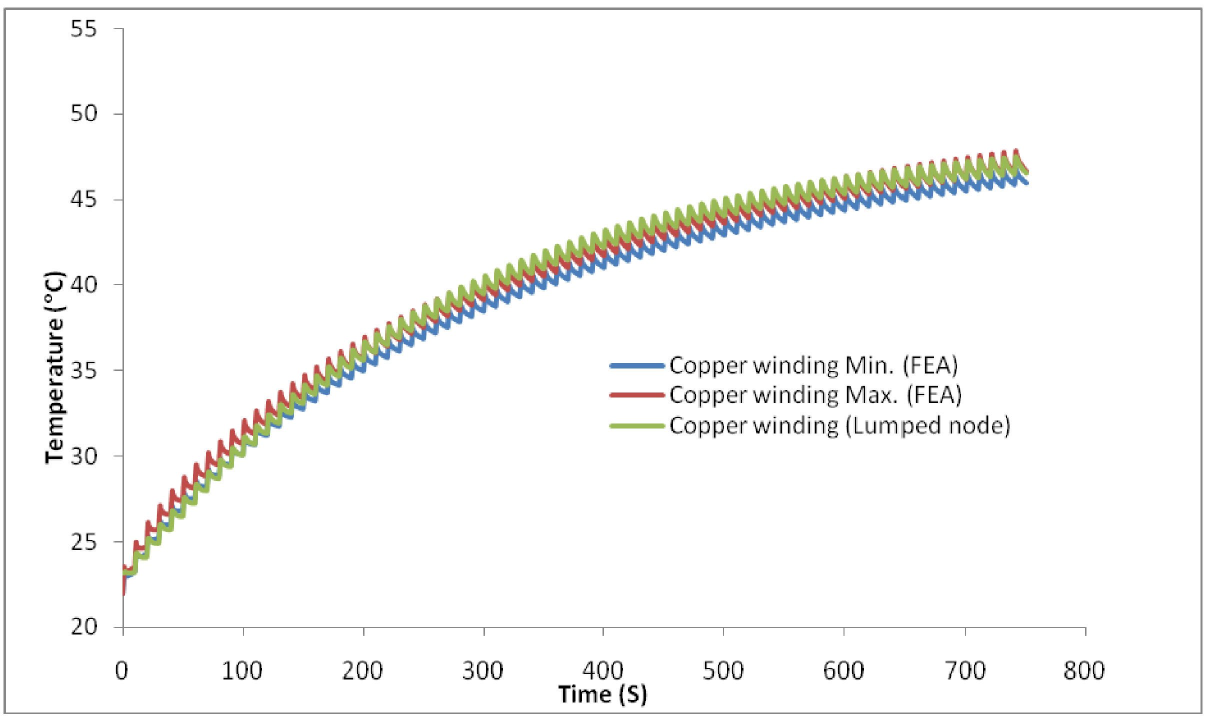

Figure 10. Winding temperature comparison (FEA and Lumped node)

The excellent agreement between ANSYS results and lumped-node model proves that this model is an effective alternative to computational intensive FEA simulation. The lumped node model is

much faster to obtain the results (less than a minute compared to 20 hours on same computer for 750 seconds of heat load profile). It can also be easily incorporated into lumped node electromagnetic motor model to do the multi-physics simulation.

CONCLUSIONS

The lumped node thermal network is a feasible approach to simulate the mission-level EMA thermal performance. A new lumped node modeling technique which is based on tuning the R and C values with the FEA results is developed in this work to overcome the difficulty in obtaining the R and C parameters in the motor thermal network. The model built with this method can be incorporated into lumped node electromagnetic simulation code to perform the mission-level real-time simulation of the whole EMA.

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